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Tectonic inheritance of the Indian Shield: New insights from its elastic thickness structure

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ABSTRACT

A new evaluation of the elastic thickness (Te) structure of the Indian Shield, derived from isotropic fan wavelet methodology, documents spatial variations of lithospheric deformation in different tectonic provinces correlated with episodic tectono-thermal events. The Te variations corroborated by shear velocity, crustal thickness, and seismogenic thickness reveal the heterogeneous rheology of the Indian lithosphere. The thinned, attenuated lithosphere beneath Peninsular India is considered to be the reason for its mechanically weak strength (<30 km), where a decoupled crust–mantle rheology under different surface/subsurface loading structures may explain the prominent low Te patterns. The arcuate Te structure of the Western Dharwar province and a NNE-trending band of low Te anomaly in the Southern Granulite Terrane are intriguing patterns. The average Te values (40–50 km) of the Central Indian Tectonic Zone, the Bastar Craton, and the northern Eastern Ghats Mobile Belt are suggestive of old, stable, Indian lithosphere, which was not affected by any major tectono-thermal events after cratonic stabilization. We propose that the anomalously high Te (60–85 km) and high S-wave velocity zone to the north of the Narmada–Son Lineament, mainly in NW Himalaya, and the northern Aravalli and Bundelkhand Cratons, suggest that Archean lithosphere characterized by a high velocity mantle keel supports the orogenic topographic loads in/near the Himalaya. The Te map clearly segments the volcanic provinces of the Indian Shield, where the signatures of the Reunion, Marion, and Kerguelen hotspots are indicated by significantly low Te patterns that correlate with plume- and rift-related thermal and mechanical rejuvenation, magmatic underplating, and crustal necking. The correlations between Te variations and the occurrence of seismicity over seismically active zones reveal different causal relationships, which led to the current seismogenic zonation of the Indian Shield.

1. Introduction

The Indian Shield has a complex tectonic framework developed through a long history from Archean to Cenozoic, and thus is ideal for re-investigation of correlations between the mechanical strength of the continental lithosphere, the thermal age of different tectonic provinces, and ambient tectono-magmatic processes. The Indian Shield has a variable lithospheric structure, because it formed by the amalgamation of many different tectonic domains with very different lithology, structure and evolution. Accordingly, realistic rheological models from surface observations (e.g., gravity anomalies, seismic images) should reflect the roles played by different factors (e.g., variable composition, structure, geothermal gradient, and stresses acting on the plate) that influenced the degree and style of lithospheric deformation.

The outer layer of the Earth is able to support topographic loads, which may fail in both brittle and ductile modes. The integral mechanical strength of the lithosphere, within limits imposed by its brittle–ductile rheology (Burov and Diament, 1995), is often expressed in terms of effective elastic thickness (Te). Brittle strength increases linearly with depth (Byerlee, 1978), whereas ductile strength is non-linearly dependent on strain rate, temperature and lithology (Carter and Tsenn, 1987). Therefore, the spatial variations and gradients in Te can be used as powerful diagnostic tools to link the loci of strain accumulation and brittle failure (e.g. seismicity, faulting) (Audet and Burgmann, 2011; Audet and Mareschal, 2007). Because Te depends on thermal state, composition, and geometry of the lithosphere, and on the stresses acting on it (Burov and Diament, 1995; Lowry and Smith, 1995), its lateral variations on a regional scale can be mapped to explore the correlations between temporal evolution and spatial configuration of the lithosphere (Audet and Mareschal, 2004; Simons et al., 2000, 2003; Tassara et al., 2007; Watts, 2001).

There has been much debate about the meaning of Te for continental studies, where the rheological properties of the lithosphere are vertically and laterally heterogeneous. The elastic thickness in oceanic regions has values between nil and 65 km, which approximately correspond to the depth of the 450 °C isotherm (Watts, 1992). In contrast, the continents exhibit a Te range as high as ~80 km in stable regions (Watts and Burov, 2003) and as low as ~5 km in young and tectonically active regions (Watts, 2001). Although a few studies have suggested a possible

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correlation between Te and age of the lithosphere in Europe (Perez-Gussinye and Watts, 2005) and Australia (Simons and van der Hilst, 2002), most have demonstrated that mechanical strength is not always controlled by the first order age of the lithosphere. Te may be influenced by many factors including localized brittle failure of crustal rocks under deviatoric stress (Lowry and Smith, 1995), “sandwich” deformation (decoupling) when a weak ductile layer in the lower crust does not allow bending stresses to be transferred between strong brittle layers (Burov and Diamant, 1995), “frozen” deformation by a lattice-preferred orientation of olivine as a result of increased melt production within the upper mantle (Kirby and Swain, 2006; Simons et al., 2003), and large-scale tectonic features and faults (Audet and Mareschal, 2004). Te has been broadly used as a key proxy for the rigidity of the lithosphere, and correlated with shear wave velocity (Perez-Gussinye et al., 2007), surface heat flow (Lowry and Smith, 1995), seismogenic thickness (McKenzie and Fairhead, 1997; Watts and Burov, 2003) and seismic anisotropy (Audet and Mareschal, 2004; Nair et al., 2012).

Earlier Te estimates in the Indian Shield were performed by forward modeling techniques along one-dimensional profiles, but they failed to capture the spatial variations. Karner and Watts (1983) and Lyon-Caen and Molnar (1983) employed forward modeling of the Bouguer gravity anomaly over the Ganges basin, and suggested that Te of the continental lithosphere was high (Te ~ 80–110 km). On the other hand, McKenzie and Fairhead (1997) derived considerably lower Te estimates from free-air admittance (Te ~ 24 km) and shape-fitting techniques (Te ~ 42 km). Stephen et al. (2003) demonstrated the correlation of Te with maximum horizontal stress orientation and heat flow measurements of the South Indian Shield. They employed discrete prolate spheroidal slepian sequences using the multitaper method, and derived Te values within the range of 11–16 km. Rajesh and Mishra (2004) made the first attempt to derive relative variations of mechanical strength of the Indian Shield based on transitional coherence wavelength obtained from multitaper analysis using overlapping windows of equal size. Jordan and Watts (2005) used both forward and non-spectral inverse gravity modeling techniques to estimate the spatial variation of Te within the India–Eurasia collision zone. Their Te map shows significant variations along strike of the Himalayan foreland (central region, Te ~ 70 km; east and west, Te ~ 30–50 km), and a weak Indian peninsula (low Te). Recently, Nair et al. (2012) reported a correlation between Te (ranges up to a maximum of 25 km) derived from multi-spectrogram (Bouguer coherence) analysis, and seismic anisotropy in the Indian Shield. Trivedi et al. (2012) used the isotropic fan-wavelet land–ocean deconvolution method to derive low (0–45 km), intermediate (45–70 km) and high (70–100 km) Te values within the Indian Shield. All these studies have demonstrated that the difference in the absolute value of the effective elastic thickness between competing analysis methods is significant only if proper cognizance is taken of the statistics of the estimates. Therefore, in the Indian tectonic context, a substantial upgrade of previous data using a more robust technique is required for a more consistent treatment of spatial Te variations including those associated with land–ocean transitions.

In this study we used the Morelet wavelet-based Bouguer coherence technique adopted from Kirby and Swain (2004). The technique uses a superposition of two-dimensional Morelet wavelets in a geometry termed ‘fan-wavelet’ (isotropic spectral envelope in adjacent directions within 180°), which yields isotropic wavelet coefficients for the co- and cross-spectra of gravity and topography data. Successful applications of the wavelet-based coherence method have been made in different tectonic settings including the Australian Shield (Swain and Kirby, 2006), Canadian Shield (Audet and Mareschal, 2004; Audet and Mareschal, 2007; Kirby and Swain, 2009), South American Shield (Tassara et al., 2007), South China (Mao et al., 2012), the Sumatra–Java subduction zone (Ratheesh Kumar et al., 2010), the Andaman subduction zone (Ratheesh Kumar et al., 2013), the Ninetyeast Ridge (Ratheesh Kumar and Windley, 2013), and global estimates (Audet and Burgmann, 2011). These examples demonstrate the major contribution of the present methodology in deriving the spatial variation of elastic thickness of both continental and oceanic regions. The aim of this paper is to reappraise the mechanical state of the Indian Shield and its possible correlation with other tectonic proxies to contribute to a better understanding of intra-continental deformation and geotectonic segmentation.

2. Lithospheric provinces of peninsula India

The main tectonic provinces of the Indian subcontinent are here reviewed, in order to test whether there are any relationships between them and the present Te structure. Fig. 1 depicts the generalized tectonic features of the Indian Shield, which contains five major Archean Cratons viz., Dharwar, Bastar, Singhbhum, Bundelkhand, and Aravalli (Naqvi and Rogers, 1987). All these cratons have their own uniqueness and are bounded by shear zone systems. Moreover, all these cratons are characterized by late stage mafic/dolerite dyke swarms, with an age range of 2370 to 750 Ma, intruded during periods of non-orogenic extension (Ernst and Srivastava, 2008).

The Dharwar Craton (Fig. 1) is the largest craton situated in southern India (Chadwick et al., 2000; Chardon et al., 2008; Jayananda et al., 2013). The northern part of the Craton is covered by the younger Deccan Trap volcanics. Traditionally this major Craton is sub-divided into three provinces, the western, central and eastern, based on geology and geochronology (Fig. 1). Recent works of Ishwar Kumar et al. (2013) and Santosh et al. (in press) have delineated the Karwar and Coorg Blocks (Fig. 1) respectively from the northwest and southwest margin of the western Dharwar province. The prominent NNW-trending Chitradurga Shear Zone (Chardon et al., 2008; Peucat et al., 2013) separates the Western and Central provinces. The Western Dharwar Craton mainly comprises TTG gneisses that contain high-grade meta-sediments and meta-igneous rocks of the 3350–3000 Ma Sargur Group that forms the basement of 3020–2520 Ma low-grade greenstone belts of the Dharwar Supergroup (Radhakrishna and Ramakrishnan, 1990). The Central Dharwar province mainly comprises TTG gneisses with younger granitoids such as the N/S-trending, c. 2.51 Ga Closepet batholith (Peucat et al., 2013). The Eastern Dharwar province is dominated by calc-alkaline intrusives, TTG gneisses and migmatites intercalated occasionally with low-grade schist belts. The southern margin of the Dharwar Craton is marked by a series of E–W trending shear zones (i.e. the Palghat–Cauvery shear system), which record a complex reactivation history from the latest Archaean to the Late Neoproterozoic (Chardon et al., 2008; Chetty and Bhaskar, 2006). The Archean Nilgiri block (Fig. 1), which is an uplifted granulite grade lower crust having triangular prism shape, lies within the Palghat–Cauvery shear system. Farther south is the Southern Granulite Terrane of the Madurai block, which consists of granulite and amphibolite facies gneisses and granites that range in age from Neoarchean to Neoproterozoic (Plavsa et al., 2013). The southern boundary of the southern granulite terrane is marked by the NW-trending Achankovil shear zone (Kröner et al., 2012; Naidu et al., 2011), south of which is the Trivandrum block or Kerala Khondalite Belt.

The Bastar Craton also known as the Bhandara or Central Indian Craton is bounded by the Godavari graben in the southwest and the Mahanadi graben in the northeast. The Bastar Craton is marked to the north by the Narmada–Son Lineament, to the east by the Eastern Ghats mobile belt and to the west by the Deccan Traps (Fig. 1). The Craton consists predominantly of 2500–2600 Ma TTG gneisses intercalated with meta-sedimentary rocks; several older events (3560–3510 Ma) were reported by Ghosh (2004).

The Singhbhum Craton (Fig. 1) mainly consists of the Archaean Singhbum granite (3400–3100 Ma) in its core surrounded by metamorphosed Archaean supracrustal rocks. The northern part of the Craton is bounded by the Chhotanagpur gneisses in an extension of the Central Indian Suture (CIS), also known as the Satpura Mobile Belt (Fig. 1). The eastern part of the Craton is covered by recent Bangal fan sediments.

The Bundelkhand Craton is the smallest exposed craton in the Indian Shield; a major part may be below Indo-Gangetic Alluvium.